nEXO Experiment and Its Photodetector R&D

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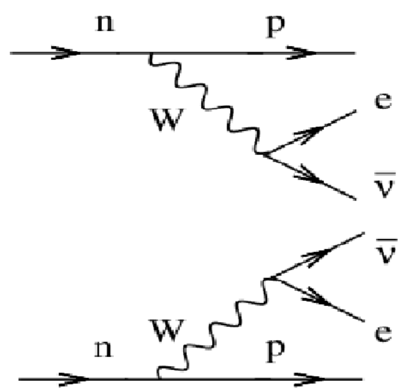
DUNE Module of Opportunity Workshop
Brookhaven National Lab

Double Beta Decay

Maria Goeppert Mayer



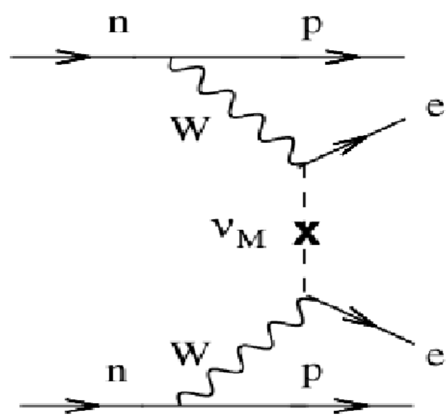
Two neutrino double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1935 Maria Goeppert Mayer first proposed the idea of two neutrino double beta decay

1987 first direct observation in ^{82}Se by M. Moe

Ettore Majorana



Neutrinoless double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1937 Ettore Majorana proposed the theory of Majorana fermions

1939 Wendell Furry proposed neutrino less double beta decay

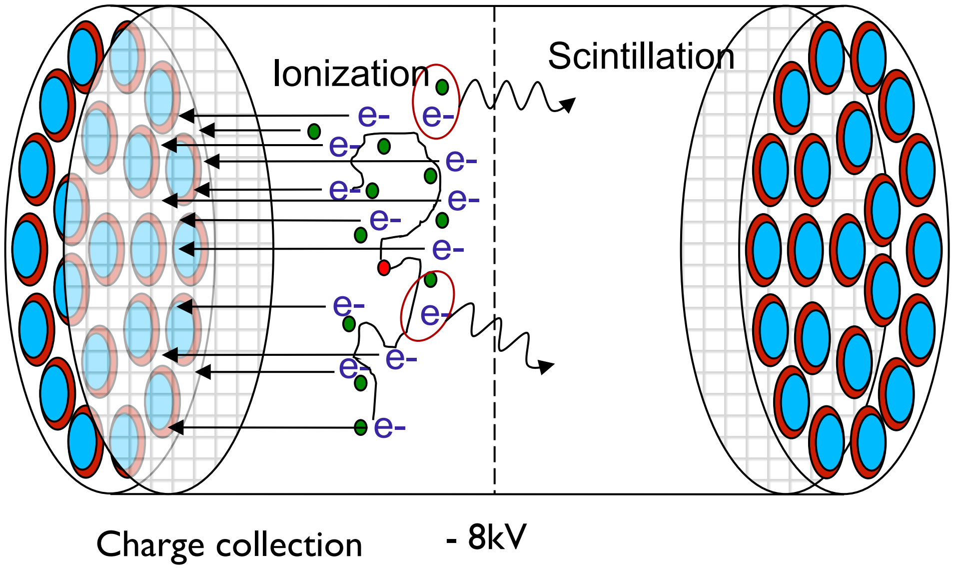
The search continues….

Observation of 0νββ:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Use Liquid Xenon Time Projection Chambers (TPC) to Search for $0\nu\beta\beta$ Decay

- Xe is used both as the source and detection medium.
- Simultaneous collection of both ionization and scintillation signals.
- Full 3-D reconstruction of all energy depositions in LXe.
- Monolithic detector structure, excellent background rejection capabilities.



Example of TPC schematics (EXO-200)

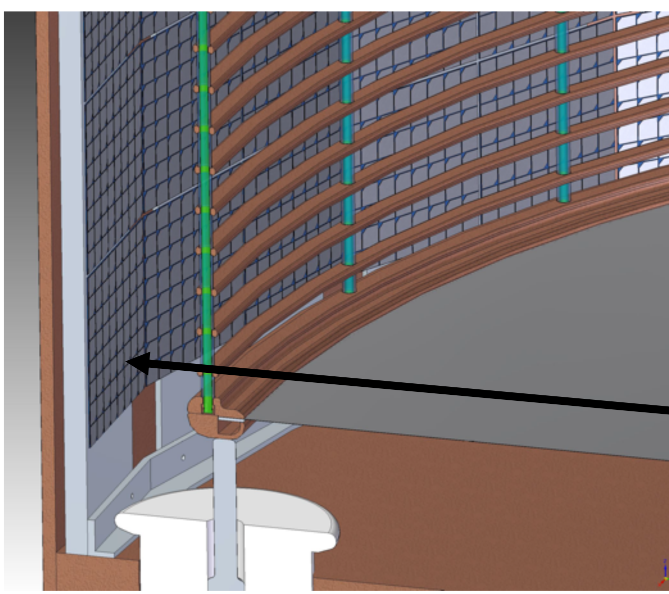
EXO-200 is a LXe detector with ~110 kg active volume, operated from 2011-2018. It has demonstrated key performance parameters for $0\nu\beta\beta$ search, and has set a lower limit on the $0\nu\beta\beta$ half-life at 3.5×10^{25} yrs with its entire dataset.

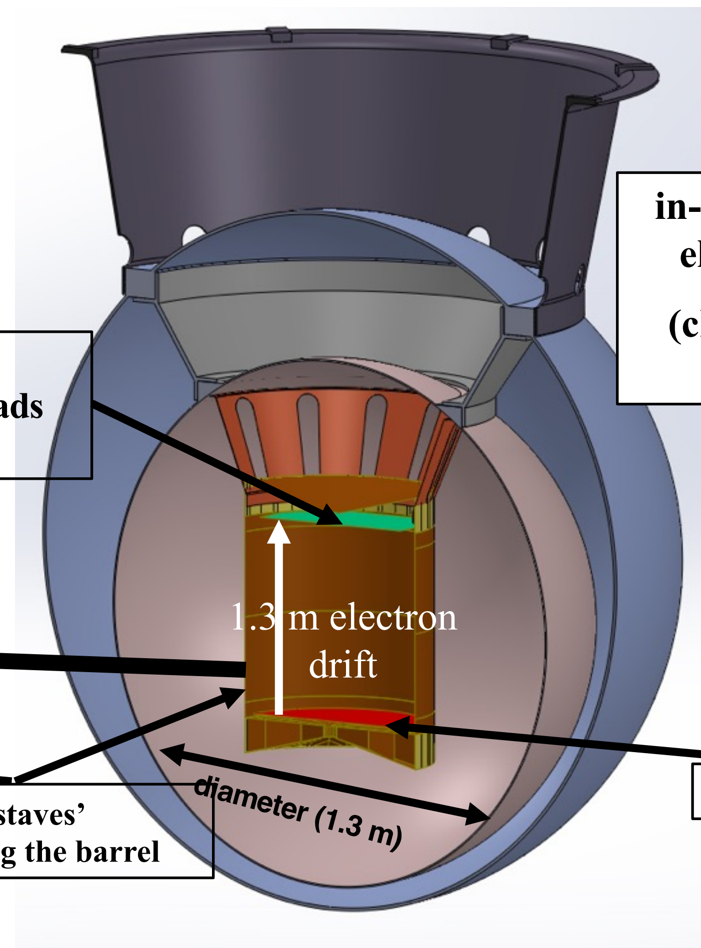
nEXO is a proposed ~ 5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach $0\nu\beta\beta$ half-life sensitivity of ~ 10^{28} yrs.

Pre-Conceptual Design of nEXO

- 5 tones of single phase LXe TPC.
- Ionization charge collected by anode.
- 178nm lights detected by ~4 m^2 SiPM array behind field shaping rings.
- Combining light and charge to enhance the energy resolution.

nEXO pre-CDR, arXiv:1805.11142





Choice of Photosensor for nEXO

EXO-200 used 500 Bare APDs.

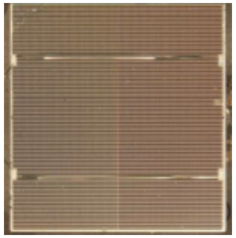
- ~ 1500 V bias
- Low gain (G~200)
- Large (dG/G)/dT ~ 5%/K
- Large (dG/G)/(dV/V) ~ 15

- VUV photon detection efficiency per area, 25%*
- Low leakage current at LXe temperature

* Accounting for inactive area

Noise goes up with increased capacitance, while signal size remains constant, difficult to reach σ/E ~ 1%.

VUV sensitive SiPM for nEXO



- 30 - 80 V bias
- High Gain (10^5 – 10^6)
- Lower (dG/G)/dT ~ 0.6%/K
- Lower (dG/G)/(dV/V) ~ 0.3

- VUV photon detection efficiency per area, up to 15%
- Dark noise and correlated noise

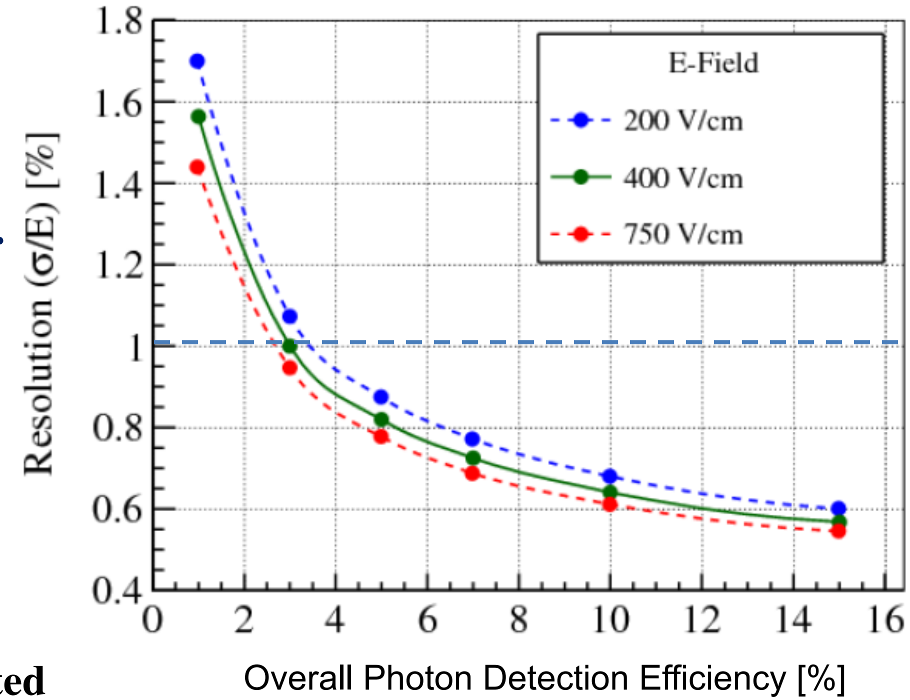
individual photon counting with high gain and low noise. Resolution limited by dark counts and correlated avalanches

Photon Detection Efficiency Requirements

To achieve 1% energy resolution, an overall 3% photon detection efficiency is required, consisting of two parts:

- **Photon detection efficiency (PDE) of SiPM**
  - **Determined by filling factor, transmittance, quantum efficiency and trigger efficiency.**
  - **Can be measured by a standalone setup.**
- **Photon transport efficiency (PTE)**
  - **Detector geometry**
  - **Reflective electrodes in TPC**
  - **Reflectivity of SiPM**

For VUV photons, more than 50% will be reflected on SiPM surface, assuming Si-SiO_2 interface.



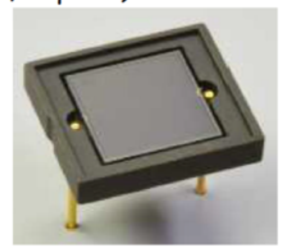
SiPM R&D for nEXO

- **SiPM PDE (at VUV region) and nuisance parameters (in cold)**
  - Stanford U.
  - TRIUMF
  - Erlangen
  - BNL
  - IHEP
  - U. Mass.

- **Reflectivity of SiPM**
  - In vacuum or N_2
    - IHEP
    - TRIUMF
  - In liquid xenon
    - U. Alabama
    - Erlangen
    - UMASS

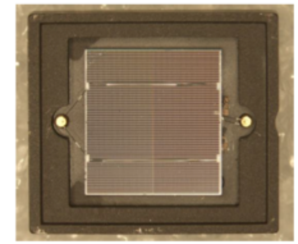
HPK VUV4 (50 & 75 μm pixel)

6x6 mm²
50 μm/pixel
14400 pixels
F=0.6



6x6 mm²
75 μm/pixel
6400 pixels
F=0.7

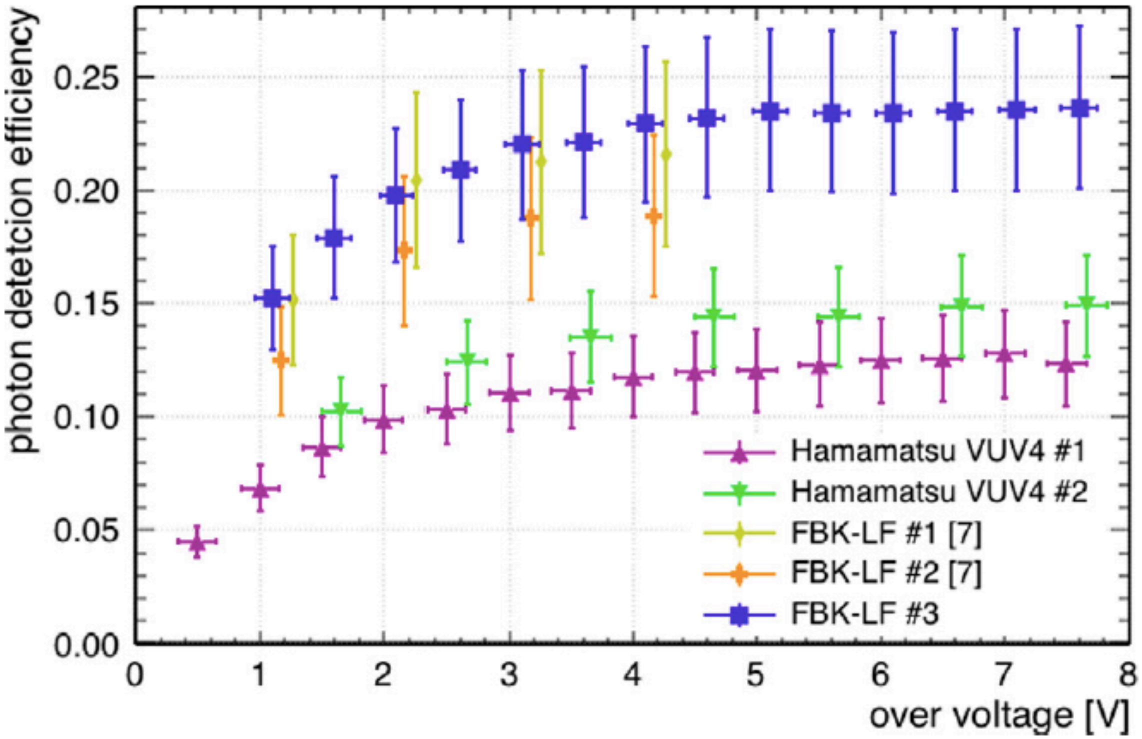
FBK VUV HD-LF



~4x(3x3)mm²
30 μm/pixel
25468 pixels
F~0.73

Tested SiPMs
- **FBK**
  - NUV, VUV-LF-HD, VUV-STD-HD
- **Hamamatsu**
  - VUV3, VUV4

PDE Measurements (TRIUMF, Stanford)

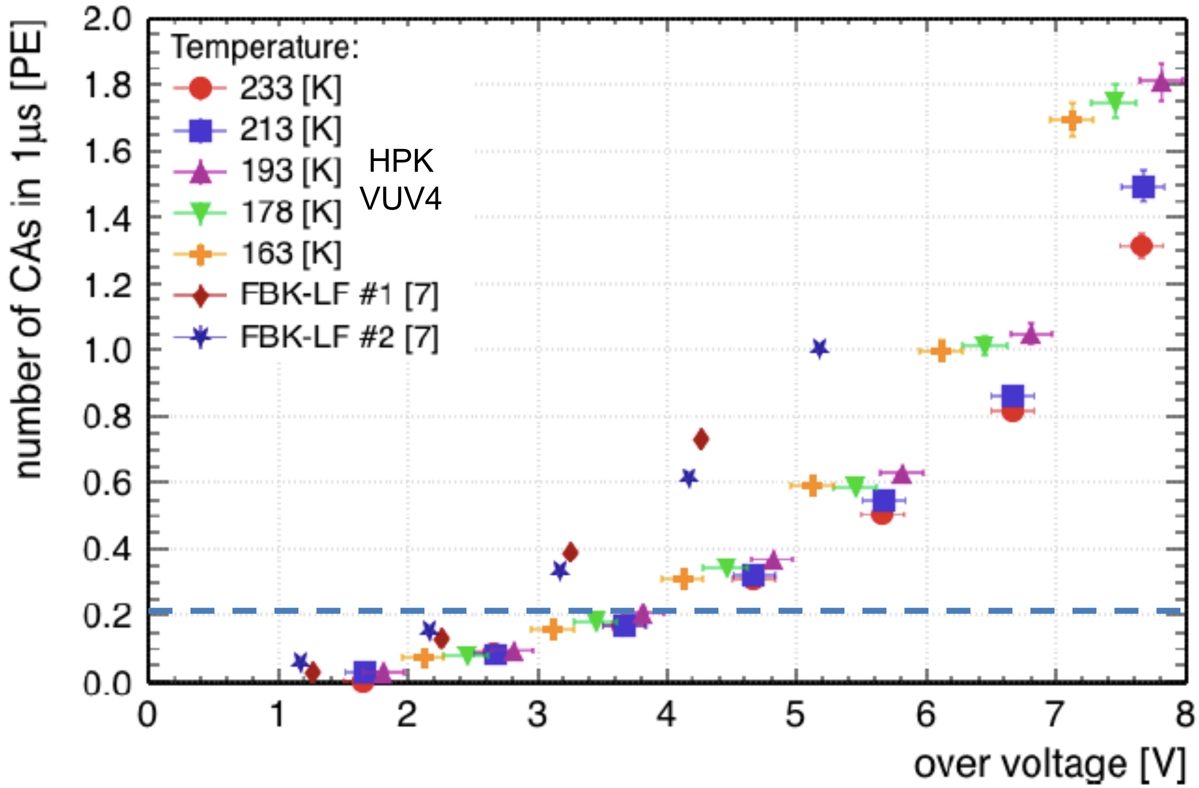


- **Center of wavelength: 180 nm**
- **FBK-VUV-LF shows higher PDE, comparing with VUV4 from Hamamatsu.**
- **The uncertainty is dominated by quantum efficiency of the reference PMT**

A, Jamil, et al. IEEE Trans.Nucl.Sci. 65, 2823 (2018)

G. Gallina et al. Nucl. Instrum. Meth., 940, 371 (2019)

Correlated Avalanches (TRIUMF, Stanford)



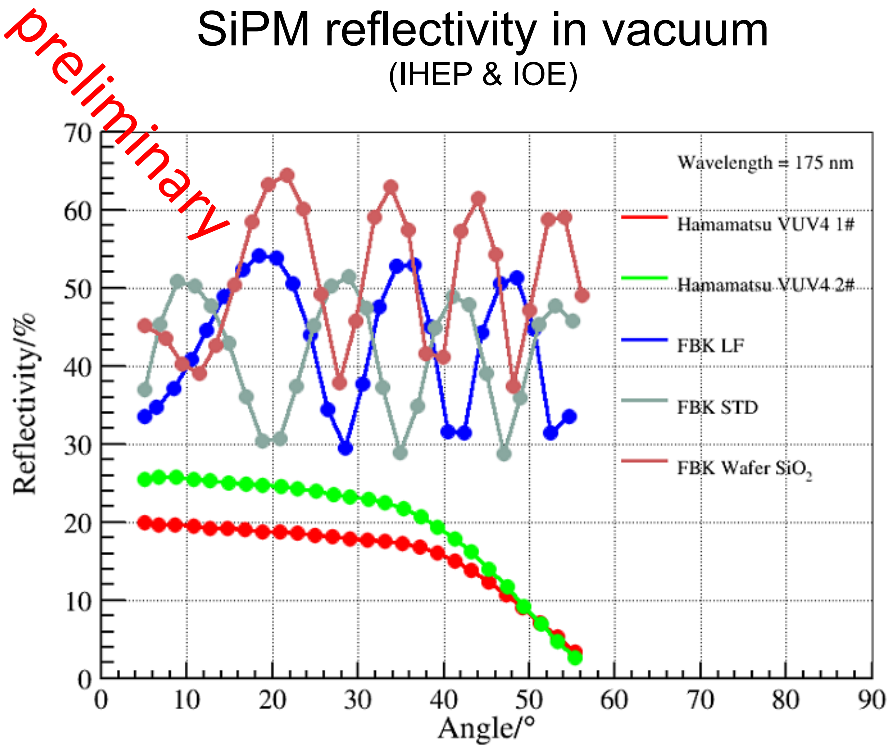
- **To achieve 1% energy resolution, the SiPM correlated avalanches (CA) need to be below 20%.**
- **VUV4 from Hamamatsu has low CA than FBK-VUV-LF, thus can be operated at a higher over-voltage.**
- **Dark noise rates for both type devices are comfortably below nEXO requirement of < 50Hz/mm^2.**

A, Jamil, et al. IEEE Trans.Nucl.Sci. 65, 2823 (2018)

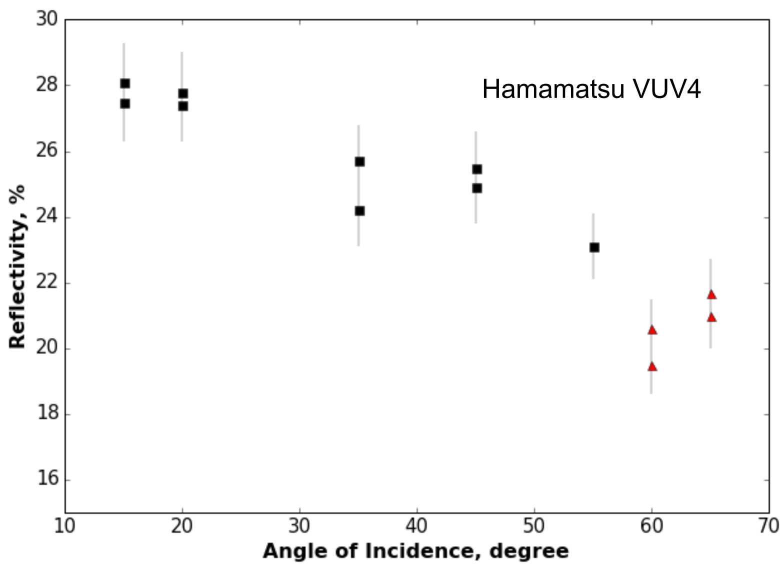
G. Gallina et al. Nucl. Instrum. Meth., 940, 371 (2019)

Reflectivity Measurements

SiPM reflectivity in vacuum
(IHEP & IOE)



SiPM reflectivity in liquid xenon
(U. Alabama)

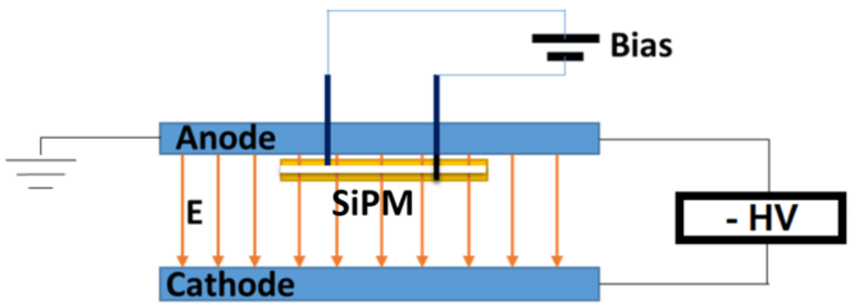


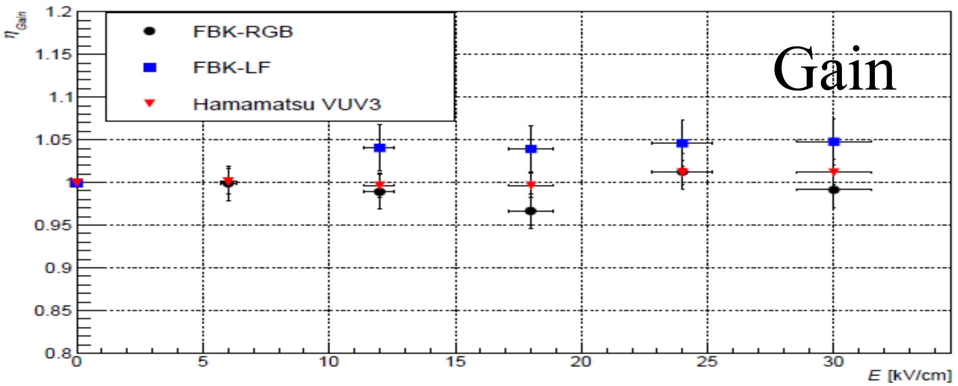
- Oscillation due to SiO_2 layer, negligible in LXe.
- Lower specular reflectivity for VUV4, comparing to FBK SiPMs.
- Similar diffused reflections between VUV4 and FBK SiPMs.

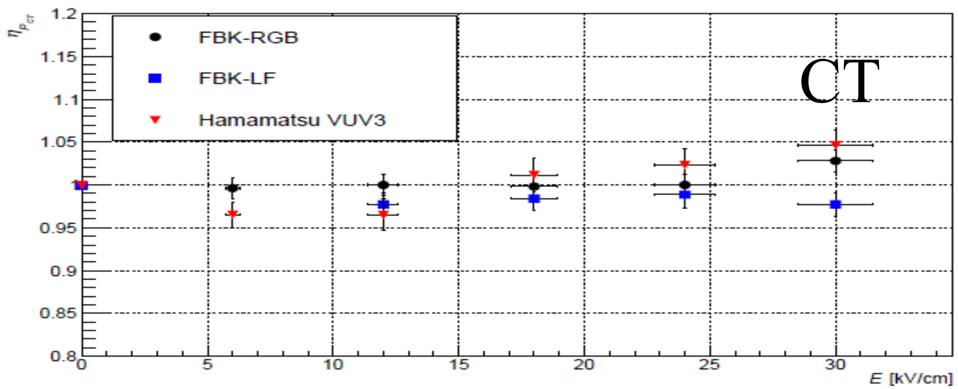
- ^{252}Cf fission sources used to produce scintillation light in LXe.
- Specular reflectivity decreases with angle of incidence.

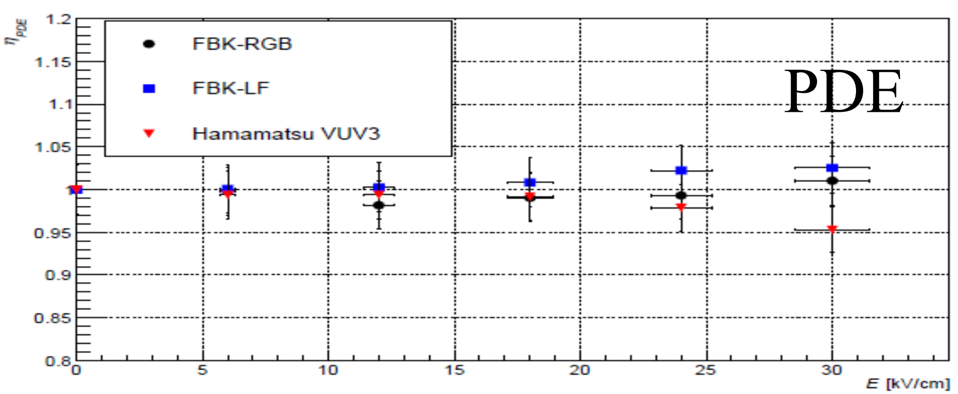
P. Nakarmi et al. arXiv:1910.06438

SiPM Performance under E-field (IHEP)







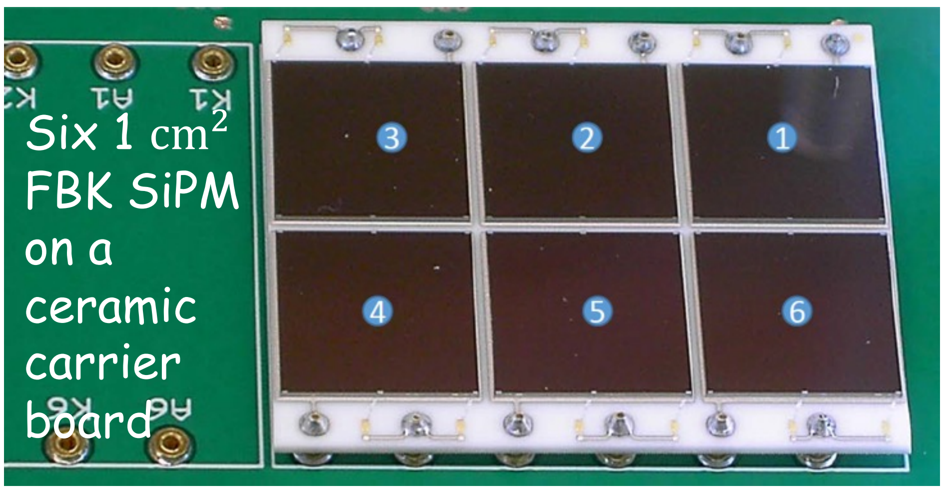


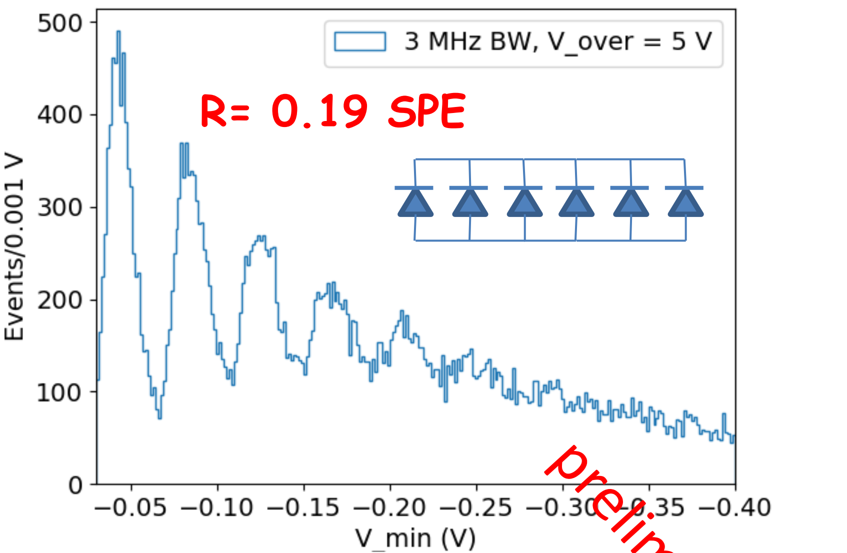
- In nEXO, SiPMs will be exposed to external E-fields up to ~20 kV/cm.
- SiPM performance in various E-fields at cryogenic temperatures (~150K) have been tested.
- The tested SiPMs show good stability under the influence of different electric field strengths.
- Need to test in LXe and understand if surface charge buildup is an issue.

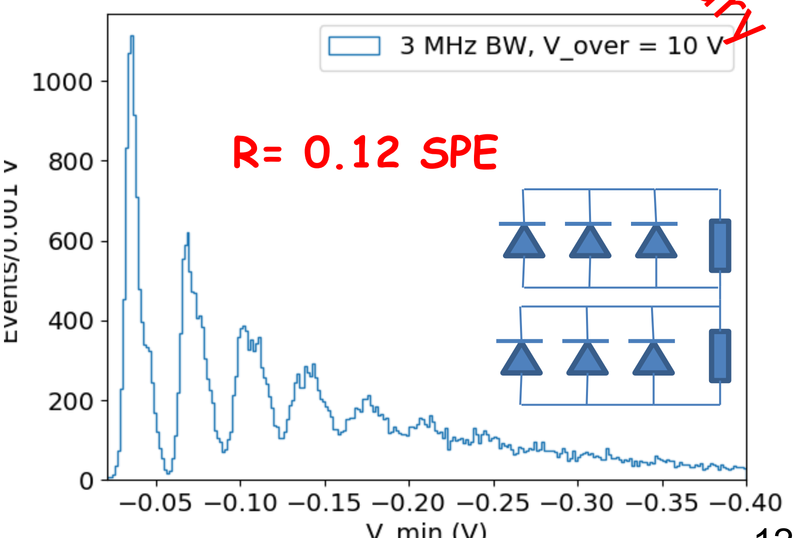
T. Tolba, et.al., JINST 13, T09006, 2018.

Large Area SiPM Readout

- **Requirements**
  - **Single photoelectron detection capability.**
  - **Low electronics noise (< 0.1 p.e.)**
- **Analog readout prototype testing**
  - **Up to 6 cm^2 SiPMs can be read out with a single front end channel in either parallel or series configuration.**
  - **2.5 mW/ch front end power meets the power requirement.**
  - **Provides valuable information for the ASIC design.**

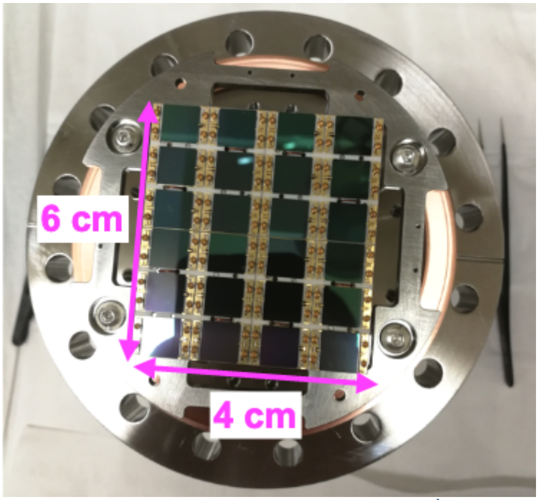




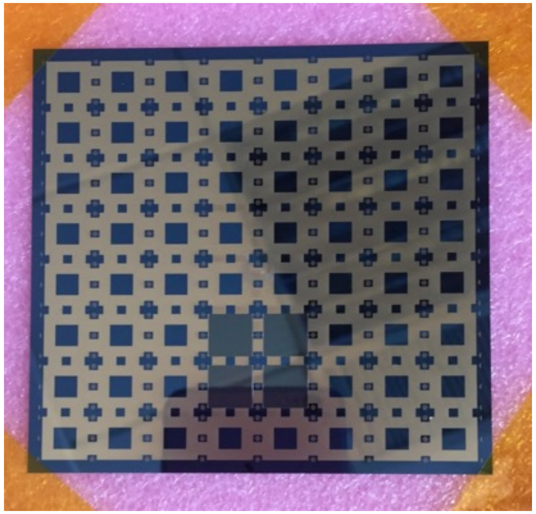


Towards Integrated SiPM Tiles

Prototype SiPM Tile (Stanford)

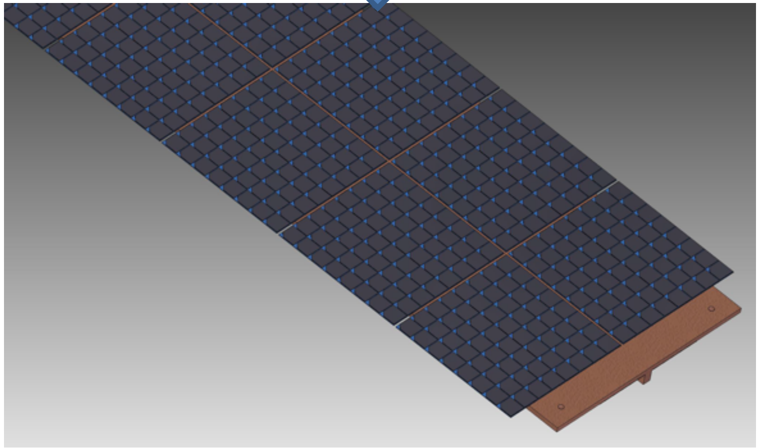


Prototype silicon interposer (IME)



ASIC (ZENON) for SiPM readout under design (BNL)

- System on Chip
- 16 channel
- Peak detection
- Analog to digital conversion
- On-chip LDOs



Conceptual design of the photo detector system underway

BNL nEXO group is playing a leading role in SiPM testing, Cryogenic ASIC design, and SiPM tile design/assembly.

Ideas and Applications for MoOD

- Direct detection of scintillation light with SiPM
  - Improve light detection efficiency if can tile the detector with SiPMs, cost of SiPM continuously to come down
  - No need for WLS, likely to improve chemical purity
  - SiPM directly sensitive to LAr scintillation light is still under development
- SiPM readout with custom cryogenic ASIC
  - Reduce the cost of SiPM readout and cabling
  - Reduce the material for the photon detector system
  - engineering cost can be lowered following the development for nEXO
- Xe doping of LAr
  - Shifting the scintillation light to improve detection efficiency
  - SiPM sensitive to Xe scintillation can be used

Summary and Outlook

- VUV sensitive SiPM is the photodetector of choice for the nEXO experiment.
- R&D efforts in the collaboration show that some devices can already meet the nEXO requirements on PDE and correlated noise.
- Reflectivity of the SiPM in vacuum and LXe is actively being investigated.
- R&D on SiPM performance in high electric field and large area readout are underway.
- nEXO is moving quickly towards a conceptual design for the photodetector system.
- Possible applications for DUNE, though all require additional R&D.

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